BACK TO ODUM: USING ECOSYSTEM FUNCTIONAL MEASURES IN STREAM ECOSYSTEM MANAGEMENT

Michael J. Paul

AUTHOR: Graduate Student, Institute of Ecology, University of Georgia, Athens, Georgia 30602-2202.
REFERENCE: *Proceedings of the 1997 Georgia Water Resources Conference*, held March 20-22, 1997, at the University of Georgia, Kathryn J. Hatcher, Editor, Institute of Ecology, The University of Georgia, Athens, Georgia 30602-2202.

Abstract. Ecosystem management, fast developing as a conceptual framework for modern resource management, presents an opportunity to develop and implement new tools to measure resource condition. Stream ecosystem ecologists have developed a number of techniques for measuring ecosystem function that can be adapted for use by resource managers. Among these are food web analysis, leaf decomposition, nutrient cycling, ecosystem metabolism, and stormwater response. This paper discusses these functional measures and how they can be used in Georgia to a) provide more information on stream condition, b) serve as robust indicators for rehabilitation success, and c) improve public interest in water quality. A simple cost analysis indicates that the price of some ecosystem functional measures is commensurate with current techniques.

"Society needs and must find as quickly as possible, a way to deal with the landscape as a whole, so that manipulative skills (that is, technology) will not run too far ahead of our understanding of the impact of change."

- E.P. Odum, 1969

INTRODUCTION

There are a number of tools, from chemical monitoring and geomorphic analysis to insect and fish bioassessment, currently used by water resource managers to measure stream quality. With government agencies committed to developing watershed management and ecosystem management plans, there is the possibility to include new or different techniques into resource management. The goal of this paper is 1) to familiarize the reader of some of the techniques used by stream ecosystem ecologists to study whole stream systems, 2) to talk about their usefulness for current resource management, and 3) to provide a partial economic analysis of these alternatives.

ECOSYSTEM TECHNIQUES

Ecosystem ecology has evolved over the past 40-50 years. In that time, theories about the importance of ecosystem function, the movement of matter and energy through an ecosystem, and ecosystem structure, the biotic and abiotic elements supporting that function, have matured. With that maturation have come various techniques for measuring and analyzing both function and structure of ecosystems. For stream ecosystems, there are several measures, developed by ecosystem ecologists, which could be used by managers today. Some of the more common techniques used include food web analysis, decomposition, nutrient cycling, ecosystem metabolism, and storm response.

Food Web Analysis

Food webs are the set of all interactions among members of an ecosystem. These most commonly include both direct energetic relationships (A eats B) and indirect relationships (A chases B and causes reduced consumption of C by B) (Polis 1994). Food web analysis could potentially incorporate known feeding relationships with bioassessment data. These, together with information about the energetic base of the system (e.g. algae, leaves, wood, macrophytes, etc.), would help determine if the community structure of a disturbed stream represents that of a healthy system. Many bioassessment protocols, for example, the Index of Biotic Integrity (IBI), incorporate this idea into the metric (Karr 1981). For more in-depth information, given available money and time - admittedly often in short supply - insect biomass along with numeric data from appropriately sampled streams would yield information on insect production. Production measures the movement of energy through the insect assemblage and indicates the insects' ability to efficiently process available carbon and transfer this to upper trophic levels (Benke 1984). Obviously, contamination, disturbance of habitat, and exotic introductions would all result in lowered insect production and shifts in community structure, perhaps sooner than shifts in bioassessment indices. The food web approach requires more information about the natural history of the organisms in streams than may be traditionally gathered, but gives a more dynamic picture of the ecosystem than can be derived from simple abundance and/or presence-absence data.

Decomposition

Decomposition of organic matter in streams is the result of many different factors (Webster and Benfield 1986). Microbial conditioning, insect consumption, and hydraulic fragmentation all contribute to decay of leaves. Disturbance in stream chemistry, temperature, and hydrology can all result in alteration of the timing and rate of leaf decomposition (Boulton and Boon 1991). Heavily eutrophied streams often show increased leaf decomposition rates (Meyer and Johnson 1983). Heightened stream temperatures can increase the metabolism of microbes and insects, leading to increased decomposition rates (Webster and Benfield 1986). Similarly, hydraulic sheer during heightened stormwater flow, often a problem in urban and suburban areas, can result in more fragmentation of leaves leading to faster decomposition (Webster et al. 1994, Paul and Meyer 1996). Increased decomposition rates can have important impacts on stream insects and therefore the whole stream food web. The life cycles of stream insects have evolved to coincide with the availability of resources, with different taxa adapted to utilize different leaf species at different levels of decomposition (Cummins et al. 1989). These carefully constructed life cycles represent the diversity in hatching and emergence times of stream insects. If the timing of leaf inputs and decay rates are substantially altered, either through riparian destruction or any of the factors described above, it is possible to see changes in the community structure and production of the stream insect community and, therefore, in the fish community as well.

Leaf decomposition rate is easily measured. Leaf packs are simply left in the stream and sampled at regular intervals over a period of a few months. Insects can be saved, (in fact, leaf packs are a recommended technique for collecting insects), or discarded and the leaf dry weight is simply regressed against time to give a decay rate. This has been one of the most intensively studied areas of stream ecosystem ecology and representative rates for all sorts of different leaf types in different parts of the country are published.

Nutrient Cycling

The cycling of nutrients is an essential function of healthy stream ecosystems (Newbold 1992). The algal and bacterial production of healthy systems is usually limited by one or several nutrients and these exhibit very tight cycling (Allan 1995). Nutrient uptake is increased by stream water retention (lower flows, physical complexity, etc.), allowing more time for uptake to occur, and by the presence of organisms utilizing those nutrients (macrophytes, decaying leaves, etc.) (Mulholland et al. 1985, Meyer 1979). Exogenous nutrient inputs are usually rapidly absorbed and utilized by these limited systems. Humans have recognized this for eons and have long utilized this to our advantage in disposing of waste. Nutrients with gaseous phases, such as nitrogen and carbon, are assimilated and mineralized out of stream ecosystems back into the atmosphere. Other elements, such as phosphorus and calcium, lack gaseous phases and are either fixed into tissue and removed and/or precipitated out of solution.

Ecologists, realizing the importance of different nutrients to the production of stream ecosystems, have developed several ways of measuring the cycling of nutrients in streams (Newbold et al. 1981). One of the more straightforward techniques involves releasing a known quantity of an active target nutrient (e.g nitrogen or phosphorus) into a stream and measuring its disappearance or uptake along a given reach of stream. The natural dilution can be corrected by releasing a non-active or conservative tracer (e.g. chloride or bromide) at the same time. By regressing the nutrient concentrations, adjusted for background and dilution, against distance downstream, the uptake length of nutrients can be calculated. This distance is related to the uptake rate for that nutrient in the stream. Eutrophication of watersheds as a result of anthropogenic inputs can lead to lengthening of nutrient uptake lengths as the system becomes saturated and limited by some other nutrient. Also, heightened stormwater flows will lead to greater export of nutrients and reduced retention, as will channelization and removal of physical retention structures (e.g. snags, boulders, macrophyte beds, etc.). Similarly, changes in light levels, temperature, hydrology, or any other factor that can affect plants or bacteria, will alter uptake lengths.

Ecosystem Metabolism

Ecosystem metabolism is the difference between gross primary production (the sum of all oxygen producing photosynthesis in the stream) and community respiration (the sum of all oxygen consuming metabolism in the stream) (Odum 1956). Metabolism indicates the efficiency with which the stream biota are producing and utilizing fixed carbon. Fixed carbon can come either from sources out of the stream (e.g. leaves, groundwater dissolved organic carbon) or from sources within the stream (e.g. algal primary production, macrophyte primary production). Any change in the supply of these sources can potentially disturb stream metabolism. Nutrient enrichments increase primary production and this can subsequently fuel higher respiration. Changes to stream morphology may result in less storage of organic matter, thus reducing the amount of respiration from the metabolism of that carbon. If light data is also available, then the production per photon of light energy, or production efficiency, can also be calculated. This may be greatly reduced when algae or macrophytes are stressed by chemical contamination. Metabolism can be measured using metabolic chambers or light and dark bottles, but these often miss the very active sediment community and the results are difficult to extrapolate to the whole stream. The best method is the one- or two-station diel metabolism method (Marzolf et al. 1994). This relies on the use of oxygen probes which monitor oxygen levels at a given reach within the stream for 24 hrs. Production and respiration are then calculated from these data.

Storm Response

Most healthy ecosystems are both resistant and resilient to disturbance (Odum 1985, Schindler 1990). Streams are resistant because many of the insects and fish have ways of avoiding high flow velocities and resilient because recolonization by non-resistant species as well as algae and bacteria is very rapid (Allan 1995). One of the more common disturbances in streams is stormflow. While often viewed as a thorn in the side of field monitoring, storms actually offer unique opportunities to assess how resistant and resilient a system is to disturbance - in terms of its hydrology, nutrient cycling, metabolism, and community structure. Monitoring hydrologic flows and rainfall during storms can be used to analyze infiltration rates, quickflow, storage, and catchment yield. These simple analyses, often used, can indicate a lot about the health of the hydrology of the watershed. Analysis of nutrient concentrations during the rising and falling limbs of storms can be used to construct curves describing the discharge-nutrient concentration relationship during a storm (hysteresis). These curves, along with routine base-flow monitoring, can be used to assess the transport and loss of nutrients and sediment from stream ecosystems and their surrounding watersheds. Lastly, monitoring insect communities before and after storms for some period can indicate their resistance and resilience. Healthier systems ought to rebound faster after disturbance, although studies of this hypothesis are lacking (Holling 1973, Schindler 1990, Tilman 1996). Severely degraded watersheds may take quite a long time to recover. In addition, any of the other measures - food webs, leaf decomposition, nutrient cycling, and metabolism can be measured before and after storms to measure the resilience of the stream to disturbance. Healthy streams would be expected to have similar rates before and after storms, as opposed to unhealthy systems which would be more highly variable and take longer to return to the same level of organic matter processing and nutrient cycling.

USING ECOSYSTEM TECHNIQUES IN MANAGEMENT

The techniques described above were developed primarily to understand the nature of material and energy flow through stream ecosystems, largely to answer questions of academic importance to ecologists interested in these data. While not esoteric, they represent a perspective rarely used in management. So how can these measures be used in managing stream ecosystems ?

E.P. Odum hypothesized that ecosystem function was the most resistant and resilient feature of any ecosystem (Odum 1985). His theoretical ideas, while soundly based and intuitive, remained untested for many years until Schindler tested them through artificial acidification of a Canadian shield lake (Schindler 1990). He, along with his colleagues, found that long after population and community structure had been altered, the production and respiration of the lake was stable. With further stress, these functional measures finally changed, but upon removing the acid stress, it was these same functional parameters that were the first to recover. This was one of the first of few studies to support Odum's hypotheses. In this light, it would appear that ecosystem functional measures offer several unique values for resource management.

First, given the resistance of these measures, it would seem that they would be good overall indicators of the extent of ecosystem disturbance. While bioassessment data are able to more quickly indicate disturbance effect, it is unclear from their results not only in which direction the system has been altered, but also the extent to which it has been altered. Ecosystem functional measures would allow an assessment of the trophic directional change. In addition, they would offer information about the alteration of particular material cycles. Most importantly, given the results of Schindler (1990), change at this level would indicate the extent to which a system has been affected by disturbance (see also Holling 1973). These kinds of information would leave managers in a better situation to understand the disturbance and to plan rehabilitation.

Second, given the resilience of ecosystem function or its tendency to be among the first attributes of a system to recover, it would seem appropriate to use these measures in monitoring rehabilitation projects. If indeed the goal is to rehabilitate a stream to a self-functioning system, it seems most natural to employ measures best associated with self-functioning behavior. With appropriate regional reference data from least disturbed systems, ecosystem functional measures would serve best in this capacity. Also, they may be among the most timely and robust in supporting conclusions about the success of a project. Certainly, given the functional redundancy and natural fluctuations within biotic communities, it may be quite some time before bioassessment metrices reach a level commensurate with "successful rehabilitation", whereas ecosystem functional measures may indicate more quickly, the success of a particular practice. Admittedly, rehabilitation ecology is in its infancy and data on the efficacy of this approach are lacking.

Lastly, it has been shown that people respond to the ideas of ecosystem health and ecosystem integrity, even though the details of these concepts are argued in academic circles. Parallels can be easily drawn between the human body and its organ systems and stream ecosystems and their various functional systems. While individuals may not appreciate the importance of a darter or mayfly, they may understand the importance of a healthy metabolism, or proper functioning of the waste removal system - nutrient cycling. I am not advocating anthropomorphizing the entire field of resource management, but simply arguing that ecosystem functional measures may have social value for managers in addition to their enormous biological value (Schrader-Frechette 1994).

These measures could easily be worked into current agency programs with the assistance of experienced or trained technicians. Most of the techniques are far less labor intensive then biotic sampling and require far less technical expertise., although data interpretation can be as difficult. In addition, many could be combined with routine monitoring. For example, leaf packs could be used to both attract insects for biomonitoring and be used to calculate decay rates. Also, multiprobes used for routine sampling of streams could be easily adapted with field logging capability for use in providing more complete daily average stream chemistry data as well as diel metabolism data Lastly, using subsamples of some insect samples for biomass estimates and gut content assessments could be easily done to provide informative secondary production and food web data. While it is clear that many agencies are already constrained by understaffed, underfunded laboratories, it is not clear that rearranging sampling protocols to provide for some ecosystem functional measures could not be easily realized.

THE COST OF MEASURING FUNCTION

The cost of ecosystem functional data may not be so extreme as one might imagine. Given the high cost of field labor, biotic sampling techniques, insect and fish identification, water chemistry evaluation, and other associated costs of current management, some functional measures are rather inexpensive. I will highlight the costs associated with leaf decomposition measures, diel metabolism, and nutrient uptake measures and compare them to the costs of insect identification.

Leaf decomposition is perhaps, the least expensive data per dollar. Leaves can be easily collected in an afternoon, leaf bags (plastic large mesh produce bags) cost less than 1 cent each when purchased in bulk, and fishing line for anchoring the leaf packs in streams is inexpensive. Leaf packs can be constructed for a study in 3 hours. The labor associated with processing the leaf packs is the greatest expense. Each pack requires 30 min to rinse, separate insects for preservation in alcohol (which can/cannot be later used for biomonitoring data), dry, and ash for estimating leaf weight loss. For a thorough study, 44 bags would be required, meaning 22 hours of lab time and roughly 11 hours of field time. This comes to a total of 36 hours of technician time. Equipment (weighing pans, leaf bags, vials, ethanol, etc) comes to approximately $30. Assuming technician costs are $15/hr, one leaf decomposition study would cost approximately $570.

Diel metabolism is more costly in terms of equipment, but requires less processing time. Measurement of stream dimension for a 300m reach takes approximately 1 hr. Release of bromide and propane for estimating transport time and reaeration coefficients requires 3 hrs of field time. Analysis of propane in the lab takes 2 hours. Set-up and break-down of oxygen probes/dataloggers requires 2 hours. Analysis of oxygen data takes approximately 4 hours. Total technical time is, therefore, 12 hours for one release. Oxygen multiprobes with datalogging capability cost $7000 for two. It is hard to estimate the per use cost, but assuming you can run 10 diels per year for 4 years with the probes (probably an underestimate), that's an average cost of $176 per diel for the probes. Propane tanks and propane cost about $6 per release. Miscellaneous equipment associated with the release come to $29 (includes measurement equipment for stream and bromide measurement in-stream). The analysis of propane requires a gas chromatograph. Average cost for 30 gas samples for propane would run approximately $400. With labor and equipment analysis, the total for this analysis would come to $779 per measurement.

Lastly, nutrient releases require approximately 7 hrs of field time, 3 hours of analysis time. Nutrient costs vary by stream size and background nutrient concentrations, but average about $20 for larger, more nutrient-rich streams and $10 for smaller, less nutrient-rich streams. Equipment consists of a pump, solute meter, sampling bottles, and a cooler, as well as equipment for measuring the stream dimensions. Average equipment costs per run come to approximately $100. Nutrient analysis for NO_3 and PO_4 cost about $2-5/per sample, meaning about $123 per release. The total cost for one nutrient release would come to $383.

To measure the decomposition, metabolism and nutrient uptake rates of a stream for four seasons in one year, would cost $5788 per year. To measure the insect community alone over four seasons in the same stream, (assuming $15/hr labor for field labor and analysis time, $125/sample for identification of 5 replicate samples over four seasons) would cost approximately $4070 per year. Add water chemistry and the cost of fish surveys, and it is easy to see that functional measures may not add so significant a cost to environmental sampling as previously believed.

CONCLUSIONS

It is obvious that resource managers in the United States are limited in available resources and constrained by administrative protocols. However, the development of ecosystem management as an operational guideline for resource management has provided an opportunity to reassess the techniques used to measure ecosystem integrity or health. While I thoroughly believe many of the techniques currently employed are necessary in resource assessment, I think they may not be sufficient. Many, for example stream chemistry and one-sample insect bioassessment, provide only a static assessment of stream condition. Even then, it is often difficult to attribute the data to any functional cause. In addition, tests of the efficacy of these metrics to measure ecosystem health are lacking.

Ecosystem function has been studied for several years and several methods have been developed to measure it. Functionally based measures provide dynamic information about system condition, since they incorporate the sum of many factors within the watershed. In addition, functional data can often indicate long-term trends in system health and offer more information on possible causes of disturbance (e.g. metabolism measures can indicate both excessive algal productivity and potential dissolved carbon pollution (sewage)), providing more information for managers and an ecosystem basis for management decisions. In addition, since these measures appear among the first characteristics to return after disturbance, they are vital in stream rehabilitation as early monitors of rehabilitative success. Finally, these measures provide a more holistic management approach that may better appeal to public interest. If these moderately priced methods were to be incorporated into resource management, they may provide a way to wed ecosystem management goals with ecosystem management objectives.

LITERATURE CITED

Allan, J.D. 1995. Stream ecology: structure and function of running waters. Chapman and Hall:New York.

Benke, A. C. 1984. Secondary production of aquatic insects. Pages 289-322 *in* V.H. Resh and D.M. Rosenberg, editors. Ecology of aquatic insects. Praeger: New York.

Boulton, A.J. and P. I. Boon. 1991. A review of methodology used to measure leaf decomposition in lotic environments: Time to turn over an old leaf ? Australian Journal of Marine and Freshwater Research 42:1-43.

Cummins, K.W., M.A. Wilzbach, D.M. Gates, et al. 1989. Shredders and riparian vegetation. Bioscience 39:24-30.

Holling, C.S. 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4:1-23.

Karr, J.R. 1981. Assessment of biological integrity using fish communities. Fisheries 6:21-27.

Marzolf, E.R., P. J. Mulholland, and A. D. Steinman. 1994. Improvements to the diurnal upstream-downstream dissolved oxygen change technique for determining whole-stream metabolism in small streams. Canadian Journal of Fisheries and Aquatic Science 51:1591-1599.

Meyer, J. L. 1979. The role of sediments and bryophytes in in phosphorus dynamics in a headwater stream ecosystem. Limnology and Oceanography 24:365-375.

Meyer, J.L. and C. Johnson. 1983. The influence of elevated nitrate concentration of leaf decompsition in a stream. Freshwater Biology 13:177-183.

Mulholland, P.J., J.D. Newbold, J.W. Elwood, L.A. Ferrin, and J. R. Webster. 1985. Phosphorus spiralling in a woodland stream: seasonal variation. Ecology 66:1012-1023.

Newbold, J.D. 1992. Cycles and spirals of nutrients, *in* P. Calow and G.E. Petts, editors, The Rivers Handbook - Volume One: Hydrological and Ecological Principles, Blackwell Scientific:London.

Newbold, J.D., J.W. Elwood, R.V. O'Neill, and W. Van Winkle. 1981. Measuring nutrient spiralling in streams. Canadian Journal and Fisheries and Aquatic Science 38:860863.

Odum, E.P. 1969. The strategy of ecosystem development. Science 164:262-270.

Odum, E.P. 1985. Trends expected in stressed ecosystems. Bioscience 35:419-422.

Odum, H.T. 1956. Primary production in flowing waters. Limnology and Oceanography 2:85-97.

Paul, M.J. and J.L. Meyer. 1996. Fungal biomass of 3 litter species during decay in an Appalachian stream. Journal of the North American Benthological Society 15: 421-432.

Polis, G. 1994. Food webs, trophic cascades, and community structure. Australian Journal of Ecology 19:121-136.

Schindler, D. W. 1990. Experimental perturbations of whole lakes as tests of hypotheses concerning ecosystem structure and function. Oikos 57:25-41.

Schrader-Frechette, K.S. 1994. Ecosystem health: a new paradigm for ecological assessment ? Trends in Ecology and Evolution 9:456-457.

Tilman, D, D. Wedin, and J. Knops. 1996. Productivity and sustainability by biodiversity in grassland ecosystems. Nature 379:718-720.

Webster, J.R. and E.F. Benfield. 1986. Vascular plant breakdown in freshwater ecosystems. Annual Review of Ecology and Systematics 17:567-594.

Webster, J.R., A.P. Covich, J.L. Tank, and T.V. Crockett. 1994. Retention of coarse organic particles in streams of the southern Appalachian mountains. Journal of the North American Benthological Society 13:140-150.